

# Effect of N-fertilizer application on return flow water quality from a terraced paddy field in Northern Taiwan

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Received: 9 August 2011 / Revised: 5 October 2011 / Accepted: 10 October 2011 / Published online: 21 October 2011  
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**Abstract** Intensive use of chemical fertilizer for crops may be responsible for nitrogen and phosphate accumulation in both groundwater and surface waters. The return flow polluted by nutrients not only results in the limitation of water reuse goals but also creates many environmental problems, including algal blooms and eutrophication in neighboring water bodies, posing potential hazards to human health. This study is to evaluate the N-fertilizer application of terraced paddy fields impacting return flow water quality. Water quality monitoring continued for two crop-periods around subject to different water bodies, including the irrigation water, drainage water at the outlet of experimental terraced paddy field, and shallow groundwater were conducted in an experimental paddy field located at Hsin-chu County, Northern Taiwan. The analyzed results indicate that obviously increasing of ammonium-N ( $\text{NH}_4^+$ -N) and nitrate-N ( $\text{NO}_3^-$ -N) concentrations in the surface drainage water and ground water just occurred during the stage of basal fertilizer application, and then reduced to relatively low concentrations ( $<0.1$  mg/l and  $<3$  mg/l, respectively) in the remaining period of cultivation. The experimental results demonstrate the potential pollution load of nitrogen can be reduced by proper drainage water control and fertilizer application practices.

**Keywords** Chemical fertilizer · Return flow · Terraced paddy field · Potential pollution load

## Introduction

Fertilizers are important materials to the production potential of agricultural land, which are used to increase production potential, maintain high yield, and product quality. However, agriculture activities are probably the most significant anthropogenic non-point pollution source (Kanwar et al. 1985). The use of chemical fertilizer has negatively impacted environments in recent decades. Intensive application of fertilizer for crops is responsible for nitrate-N contamination in both groundwater and surface waters, resulting in the environmental and ecological destruction, and may pose potential hazards to human health. As a main crop in Taiwan, rice paddies account for a significant share of chemical fertilizer consumption among agriculture crops. Losses of nitrate-N from applied chemical fertilizer may be high from paddy fields as they are under a flooded condition for most of the cropping period. Nitrate-N is highly soluble, and fast moves with the water percolating to groundwater or leave out by drainage or runoff. Prediction of contamination potential of nitrate-N is complicated by the variable nature of soils, irrigation water management, and the complex set of N-transformation processes in paddy fields (Chowdary et al. 2004).

In fact, rice paddies cultivated in monsoon Asia not only provide high productivity of rice but also maintain a sustainable and environmental friendly ecosystem that suits the regional climatic and topographical conditions. Rice paddy cultivation forms unique way of life, a complex amalgamation of sustainable human activity, society, and natural environment. Moreover, paddies also support the

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convenience of life for urban city by reducing floods, recharging groundwater, lowering air temperature, reducing carbon dioxide, preventing soil erosion, and purifying water quality (OECD 1998; Tsai et al. 2003; Matsuno et al. 2006; Kim et al. 2006; Liu et al. 2010). Many field tests proved that if water with a high nitrogen concentration and was introduced into paddy fields, high nitrogen removal would be performed (Nakasone et al. 2003). However, inadequate water management also influences N losses during both storm and non-storm periods. Proper water management is required to reduce nutrient losses through surface drainage from paddy fields; such as minimum irrigation, effective use of rainfall, adoption of proper drainage outlet structures, and minimized forced surface drainage (Yoon et al. 2006).

To increase water use efficiency in Taiwan, the continuous irrigation method, which maintains a ponded water depth of 5–6 cm in rice plants except during weeding, fertilizing and harvesting, has been gradually replaced by a new irrigation scheme known as ‘rotational irrigation’ in plain area. In this scheme, irrigation water is supplied in appropriate quantities, at the ideal time and in the proper order to insure that all rice paddies receive their minimum water requirements. That is, during 5- to 8-day periods, a total of 6–8 cm water is supplied to the rice paddies only for the first day (Chen and Liu 2002). However, terraced paddy fields located in the middle and upper parts of river valleys in the mountainous area are relatively small in terms of sowing areas. Thus, mechanical cultivation is difficult herein. The extensive water management practice, continuous irrigation method is still adopted in such area. The aim of this study is to determine the effects of N-fertilizer application on the return flow water quality of terraced paddy fields. The results of the study corresponded to conventional water management practices of rice paddy fields in Taiwan. Irrigation/drainage and fertilizer application rates were all controlled by native farmers. All measurements were carried out in 2010. The results can provide governmental agencies with a basis for evaluating policies concerning the sustainability of soil fertility and groundwater resources and for developing crop nutrient management protocols of terraced rice field in mountainous areas.

## Materials and methods

### Study site/description of paddy field

The 0.75-ha experimental terraced rice field with uniform steep slope (about 25°) located in Hsin-chu county, Northern Taiwan (24°30'N, 121°24'E) was used for surface water bodies investigation while groundwater quality

parameters were monitored in observation wells (nos. 1–3) located in neighboring paddy fields (Fig. 1). The topsoil contains 45.2% sand, 31.7% silt, and 23.1% clay. The irrigation water for the experimental paddy field is directly introduced from a nearby torrent intake through pipelines, to the upper field block, and distributed via overflow to the entire blocks of the terraced paddy. The impact of fertilizer application on water quality for various water bodies including irrigation, drainage water, and groundwater was investigated during the regular cultivation period of rice in 2010. Two crops of rice paddy were planted in 2010: the first crop period was lasted for 4 months from March to the middle July while the second crop period started transplanting at the end of July and harvested in middle November. Moreover, well no. 1 was monitored in first crop period, while wells nos. 1–3 were used in the second crop period. Preparation of the rice fields started about 1 week before the rice was transplanted and the fields were usually first flooded. The amount and timing of fertilizer applications were determined by interviewing farmers in the study area. The records of agricultural activities are summarized in Table 1.

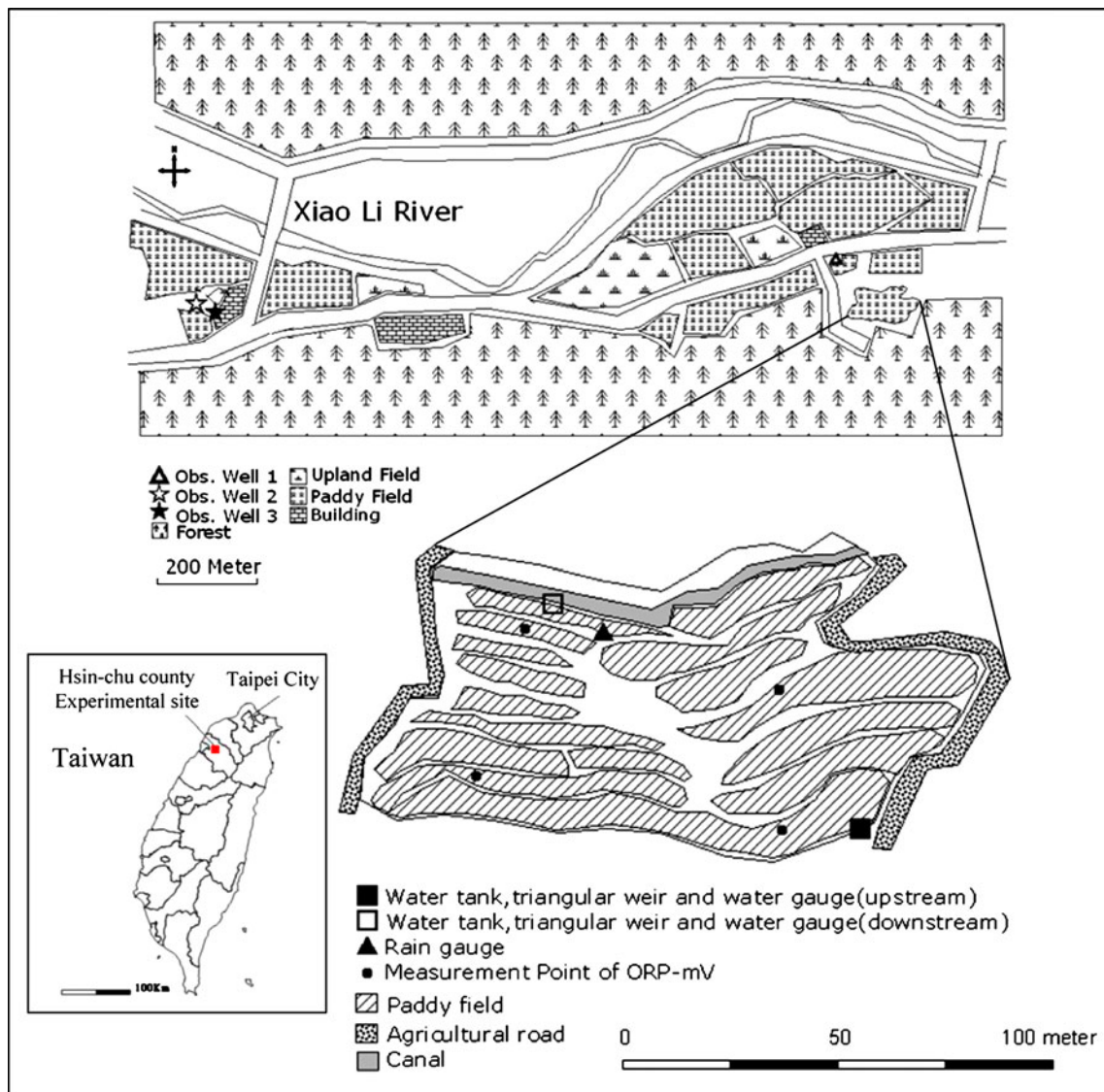
The amount of N-fertilizer applied to the paddy fields was estimated from interviewing with farmers. Urea ( $\text{CO}(\text{NH}_2)_2$ ) and ammonium sulfate  $(\text{NH}_4)_2\text{SO}_4$  were used for compound N-fertilizer. Chemical basal N-fertilizer was applied at rates of 53 and 60 kg N/ha during the first and second crop periods, respectively. Other N applications included 43 and 48 kg N/ha for tillering fertilizer and panicle fertilizer during the first and second crop period, respectively. The total amount of chemical N-fertilizer applied in this experimental paddy field ranged from 116 to 139% (the first crop), and from 142 to 173% (the second crop) of nitrogen compared to the rational application rate of chemical fertilizer for rice cultivation in north Taiwan (Agriculture and Food Agency 2005) (100–120 kg N/ha for the first crop and 90–110 kg N/ha for the second crop). The results of the study corresponded to conventional water management practices of rice paddy fields in Taiwan. Irrigation/drainage, fertilizer application, and other management practices of experimental paddy field were controlled by the farmers.

### Measurements of surface drainage

A water balance equation in a terraced paddy field is commonly used to assess runoff, as follow:

$$I + R = E + T + S + P + D + dW \quad (1)$$

where  $I$  is the irrigation supply,  $R$  is the rainfall,  $E$  is the evaporation,  $T$  is the transpiration,  $S$  is the lateral seepage,  $P$  is the percolation,  $D$  is the surface drainage or runoff, and  $dW$  is the change in flooded water depth and water storage



**Fig. 1** Schematic representation of study area and layout of experimental site in Taiwan

in the soil profile. All items were expressed in terms of mm/day. During the experimental field planted with rice in 2010, a continuous irrigation scheme was adopted to maintain the 4–6 cm flooded water layer except the periods of fertilizer application and harvesting. If heavy rainfall occurred, irrigation would be ceased to reduce runoff. An automatic rainfall recorder was set up at the downstream of the terraced field. The volumetric irrigation and discharge flux was measured using triangular weirs with water level gauges set up at the inlet and discharge point at the upper stream and downstream of the terraced field (Fig. 1).

To realize the water system comprehensively, the percolation rates measured by a double ring infiltrometer in six sites under a flooded condition ranged from 0.15 to 2.82 cm/day, with an average value of 0.91 cm/day. Reference crop evapotranspiration ( $ET_0$ ) values were

determined using the Pan Evaporation method. Pan evaporation values on a 10-day basis were collected from meteorological observatory of TREA (Tea research and extension station, Taiwan) located at about 9 km distance from the experimental site. The pan coefficient ( $K_{pan}$ ) was set to 0.82 according to the research of Chang (2007). The crop coefficients under different growth stages in Taiwan (Table 2; Kan 1979) were adopted to estimate the ET values. A rough estimation on ET values for the first and second crop periods in experimental paddy field were 304.19 and 374.98 mm, respectively.

In terraced paddy field areas with independent irrigation and drainage ditches, irrigation return flow at the outlet during cultivation seasons consists of irrigation tailwater and stormflow, lateral subsurface return flow, and bypass water, which are called visible return flow while the deep

**Table 1** Record of agricultural activities data in 2010

Date	Agricultural activities and fertilization	Remarks (kg N/ha)
First crop period		
2/20	Land preparation	
2/27	Basal fertilization	53.33
3/2	Transplanting	
3/19	Tillering fertilization	42.67
4/03	Panicle fertilization	42.67
7/18	Harvest	
Second crop period		
7/17	Land preparation	
7/24	Basal fertilization	60.0
7/28	Transplanting	
8/7	Tillering fertilization	48.0
8/17	Panicle fertilization	48.0
11/20	Harvest	

**Table 2** The crop coefficients under various growth stages in Taiwan (Kan 1979)

Days to reach growth stage	Growth stage	First crop period	Second crop period
1–15	Planting	0.5	0.9
16–30	Early vegetative	0.8	1.2
31–45	Late vegetative	1.2	1.5
46–60	Early flowering	1.3	1.6
61–75	Late flowering	1.3	1.5
76–90	Early maturing	1.2	1.3
91–105	Mid-maturing	1	1
106–120	Late maturing	0.7	0.6

percolation from ponded water is called invisible return flow. Both of which are considered to be a primary water loss for farmers. However, visible return water can be reused for irrigation or other purposes in downstream areas, and the invisible return flow percolates into an aquifer, it can also be reused for irrigation or other purposes due to pumping. Therefore, the surface drainage and percolation in paddy fields can no longer be considered an irrigation loss for current water resources management in Taiwan.

### Samplings and sample analyses

Samples of irrigation water, drainage water and groundwater were manually collected on a 2- or 3-day basis during fertilizer application period and weekly basis during non-fertilizer periods. Irrigation and drainage during irrigation periods were sampled by grab technique at the inlet and outlet of the experimental field. Before groundwater sampling, the depth of water level was measured. Then,

well purging was made by pumping to get rid of water in the well casing and to bring new water from the aquifer into the well for sampling. Finally, groundwater was sampled by a bailer. All the samples were packed into ice chests and transported to laboratory for analysis. Chemical analyses for ammonium-N (measured range from 0.00 to 4.00 mg/l), nitrite-N ( $\text{NO}_2^-$ -N, measured range from 0.00 to 1.25 mg/l), and nitrate-N (measured range from 0.00 to 60.00 mg/l) were conducted using SMART 2 colorimeter (LaMotte, USA).

### N-balance in paddy field

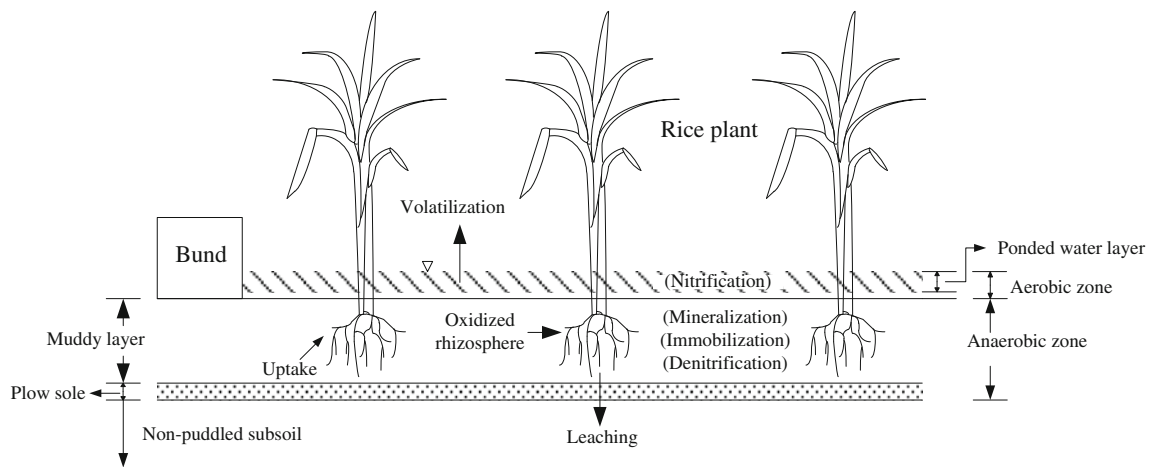
Following long cultivation periods in a paddy field, the plow sole layer, which is generally located in the 20–30 cm depth below the field surface, emerges to prevent the percolation of flooded water, and this layer significantly influences water infiltration (Wopereis et al. 1992, 1994). In a paddy field, a layer of irrigated or precipitated water lies above the top surface. Meanwhile, the top layer of the field itself comprises a low flow resistant muddy layer, followed below by a high flow resistant plow sole (hardpan layer) and a nonpuddled subsoil.

The N-loss from paddy field depends on the transport and transformations of different N species that undergo in the complicated soil/water, plant, and hydrology/atmosphere system. The flooded soil of paddy field has three distinct zones established by the prevailing redox potential of the system (Keeney and Sahrawat 1986). N-transformation reactions occur in each redox zone of a flooded rice paddy system including a layer of flooded water in which the dominant N-transformation processes are urea hydrolysis, nitrification and ammonia volatilization. The thickness of an oxidized top soil layer ranges from several mm to 10 mm below the soil surface. A reduced layer presents in the rest of the root zone in which the dominant processes are mineralization, denitrification, immobilization, leaching and plant uptake (Chowdary et al. 2004). The schematic diagram of N-transformation in a paddy environment is shown as Fig. 2. To determine the redox potential of the system, the ORP was measured at four sites before and after basal fertilizer application by the interval of 1 cm from soil surface to the 10 cm depth in the muddy layer.

## Results and discussion

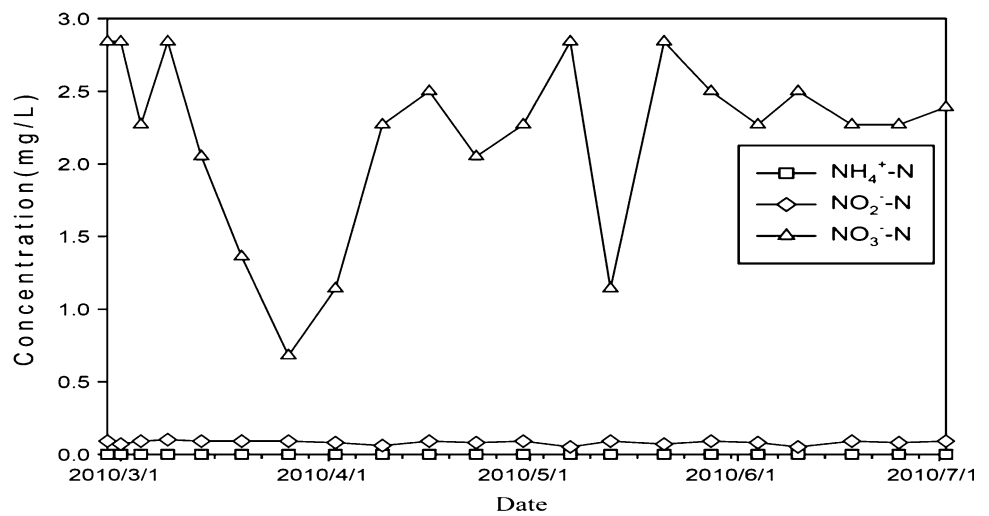
### Concentrations of nitrogen in irrigation water and irrigation return flow

Figures 3 and 4 show temporal variation of the concentrations of nitrogen in irrigation water and drainage water. The observed concentrations of nitrate-N in irrigation

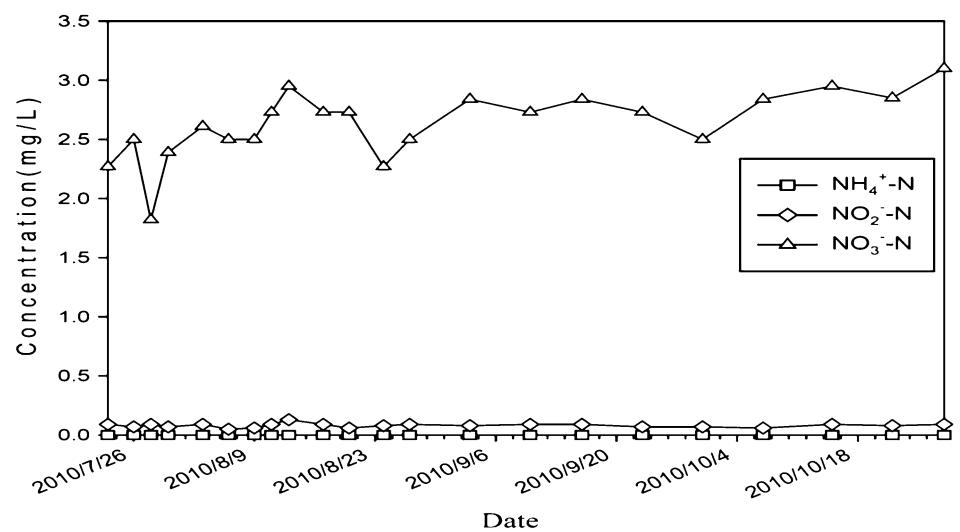


**Fig. 2** Schematic diagram of N-transformation in a paddy environment

**Fig. 3** Temporal variation of N concentrations in irrigation water during growing seasons. **a** The first crop period, and **b** the second crop period

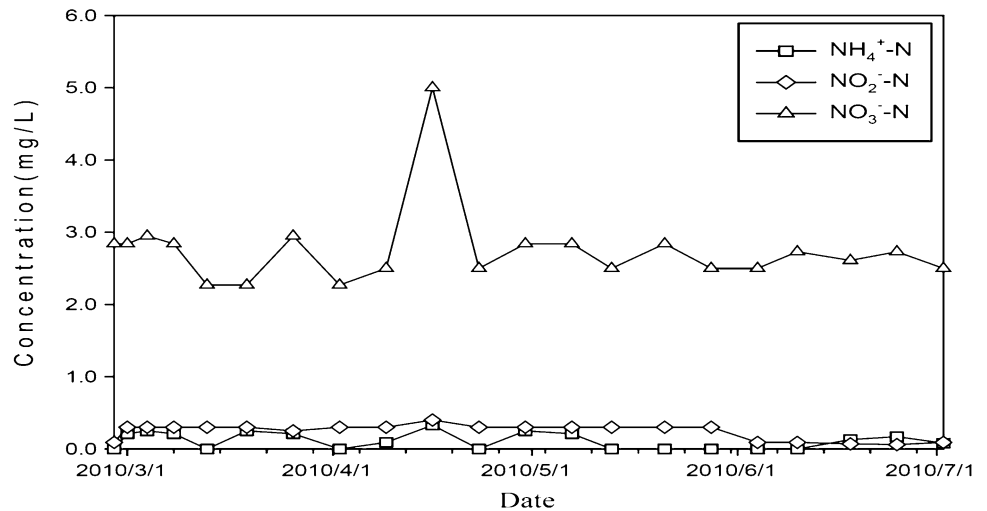


**(a)** The first crop period

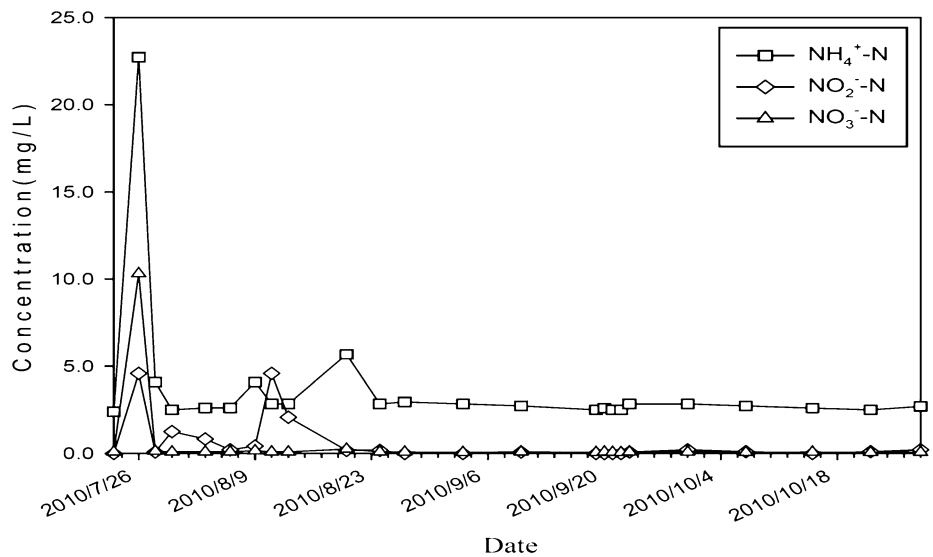


**(b)** The second crop period

**Fig. 4** Temporal variation of N concentrations in drainage water during growing seasons. **a** The first crop period, and **b** the second crop period

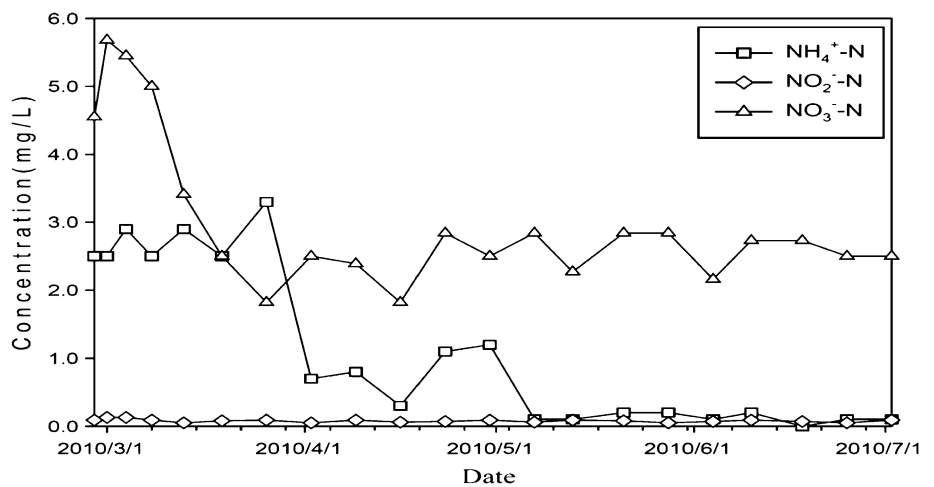


**(a)** The first crop period



**(b)** The second crop period

**Fig. 5** Temporal variation of N concentrations in groundwater during the first crop period (well no. 1)



**Table 3** Measured groundwater depths during the second crop period

Well no.	Deepest water depth (m)	Shallowest water depth (m)	Avg. (m)
1	1.52	0.75	1.13
2	2.90	2.81	2.83
3	6.31	5.22	5.56

water ranged from 0.68 to 2.84 and 2.05 to 3.10 mg/l during the first and second crop period, respectively. This was a considerably low concentration compared to drinking water quality standards in Taiwan (<10 mg/l). Moreover, no ammonium-N was detected and nitrite-N remained a low level (<0.09 mg/l). Regarding drainage water, the nitrate-N concentrations presented relatively stable trend during the first crop period. The observed nitrate-N concentrations of over 3.0 mg/l only occurred in the panicle fertilization period with the value of 5.05 mg/l. Different from the first crop season, concentrations of nitrogen were high in the early stage of basal fertilizer application but subsequently decreased until the tillering fertilization and panicle fertilization periods of the second crop season. Concentrations of nitrogen in these periods rose again but were much lower than those in the early stage of basal fertilizer application. The observed peak concentrations of nitrogen in drainage water occurred after basal fertilizer application including ammonium-N, nitrite-N, and nitrate-N could reach to 4.58, 10.31, and 22.73 mg/l, respectively. This was a quite high concentration compared to drinking water quality standards in Taiwan (ammonium-N, nitrite-N, and nitrate-N of <0.1, <0.1, and <10 mg/l, respectively). Except the three fertilizer application periods, the concentrations of nitrogen reduced to relatively low concentrations in the remaining period of cultivation, which was almost the same with irrigation water for two growing seasons.

Olson and Kurtz (1982) indicted that low soil temperatures would limit nitrification rates. Different soil temperatures may be a reason resulted in the large discrepancy of nitrogen concentrations between the first and second crop season during fertilizer application periods. Average temperatures of experimental field were 16.7°C in February and 19.0°C in March during the fertilization of first crop season, which were much lower than those of 29.9°C in July and 29.6°C in August during the fertilization of second crop season. A further long-term *in-site* measurement is suggested to solve the significant discrepancy.

#### Concentrations of nitrogen in groundwater

Owing to the characteristics of high solubility and mobility, nitrate-N derived from nitrogenous fertilizers becomes a major source of contamination of groundwater (Chowdary

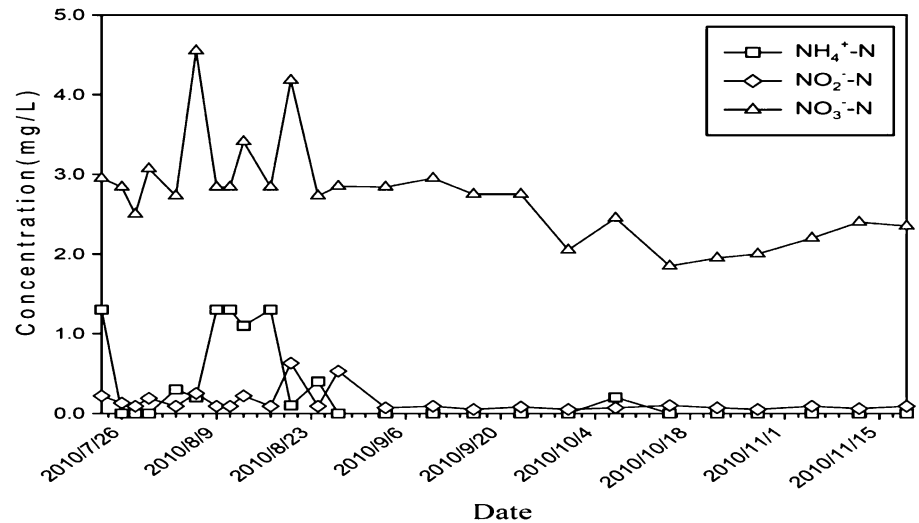
et al. 2004; Nakasone et al. 2003), but for ammonium-N, as a cation, is mostly adsorbed to the net negatively charged soil matrix (Ritter and Shirmohammadi 2001). Figure 5 shows the temporal variation of N concentrations in groundwater during the first crop period (well no. 1). Concentrations of nitrate-N were high in the early stage of basal fertilizer application (the peak value reached to 5.68 mg/l) but subsequently decreased to a relatively low concentration ranged from 1.82 to 2.95 mg/l in the remaining period of cultivation. Concentrations of ammonium-N also remained a high level during the period of basal fertilizer application (2.50–3.32 mg/l) but subsequently decreased to a relatively low concentration in the tillering fertilization and panicle fertilization periods (0.31–1.23 mg/l). Then, the concentrations of ammonium-N in the remaining periods of cultivation decreased again, but were much lower than those of fertilizer application periods.

To obtain more information about fertilizer application impacting groundwater quality, three observation wells with difference water levels (Table 3) were used during the second crop period. Figure 6 shows temporal variation of N concentrations in groundwater during the second crop period. Well no. 1 with the shallowest water depth, the more significant variation of concentrations of nitrate-N and ammonium-N could be observed. For deeper water depths of well nos. 2 and 3, concentrations of nitrate-N were almost the same with the irrigation water which could be regarded as background water quality. Also, the concentrations of ammonium-N were just detected for few times and lower than that of well no. 1 during fertilizer application periods, which mean that the major difference between the high and low contamination potential of nitrogen of groundwater is related to the length of percolation route in this area.

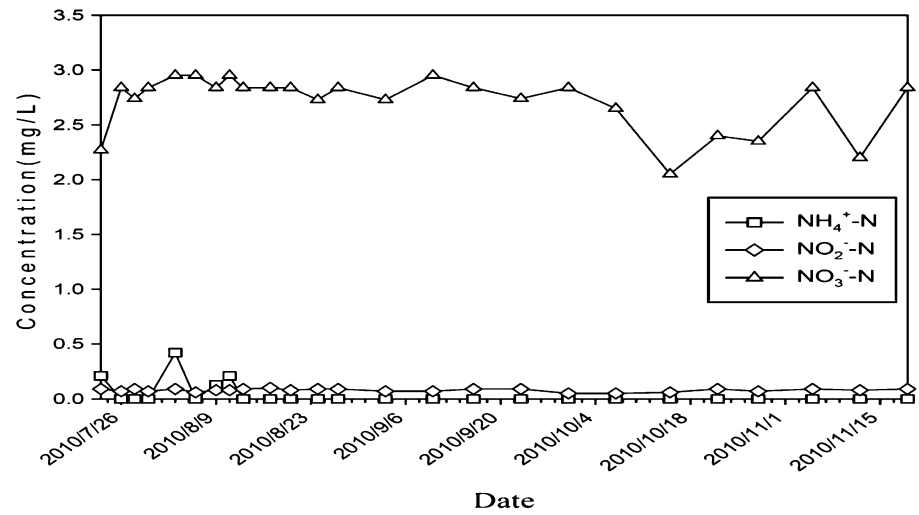
#### Redox potential of paddy field

ORP-mV varying with soil depth at four measurement sites in the experimental paddy field was measured on 1 day before/after basal fertilizer application during the first crop period (Fig. 7). The ORP values of around -200 mV were measured within the 1–10 cm depth, indicating that the redox potential of the region is dominated by the reduced condition. Yang and Chang (1997) also indicated that the *Eh* value decreased very significantly in the first 10 days after flooding treatment and with the application of chemical and organic fertilizer in the paddy soils of Taiwan. The strongly reducing conditions (below -150 mV) in the soil matrix of paddies were also observed by Schmidt et al. (2011). Therefore, the dominant N-transformation reactions could be mineralization, denitrification, immobilization, leaching, and plant uptake. Moreover, if

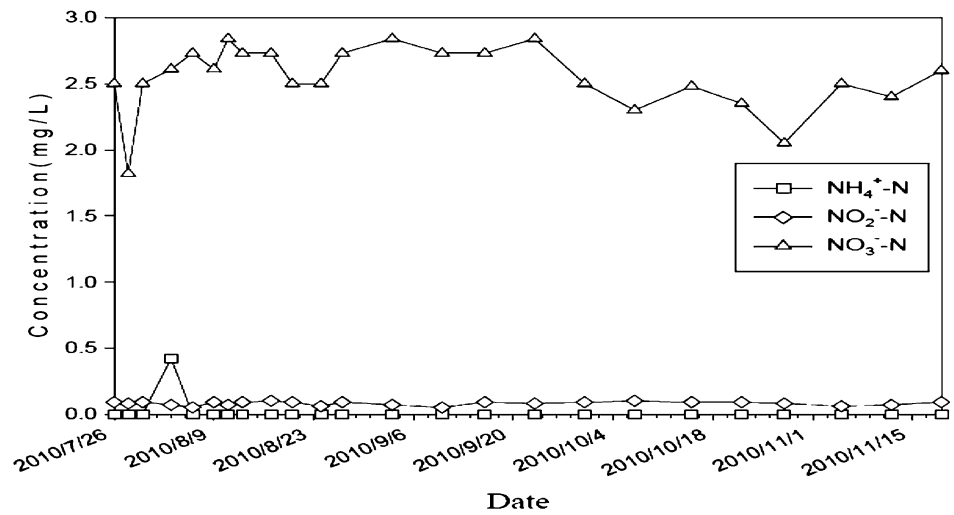
**Fig. 6** Temporal variation of N concentrations in groundwater during the second crop period. **a** Well no. 1, **b** well no. 2, and **c** well no. 3



(a) Well No.1



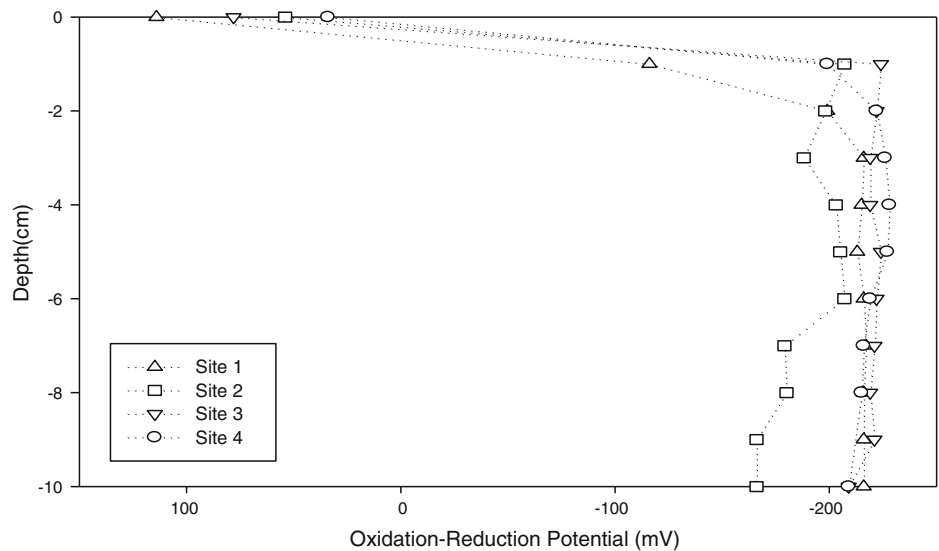
(b) Well No.2



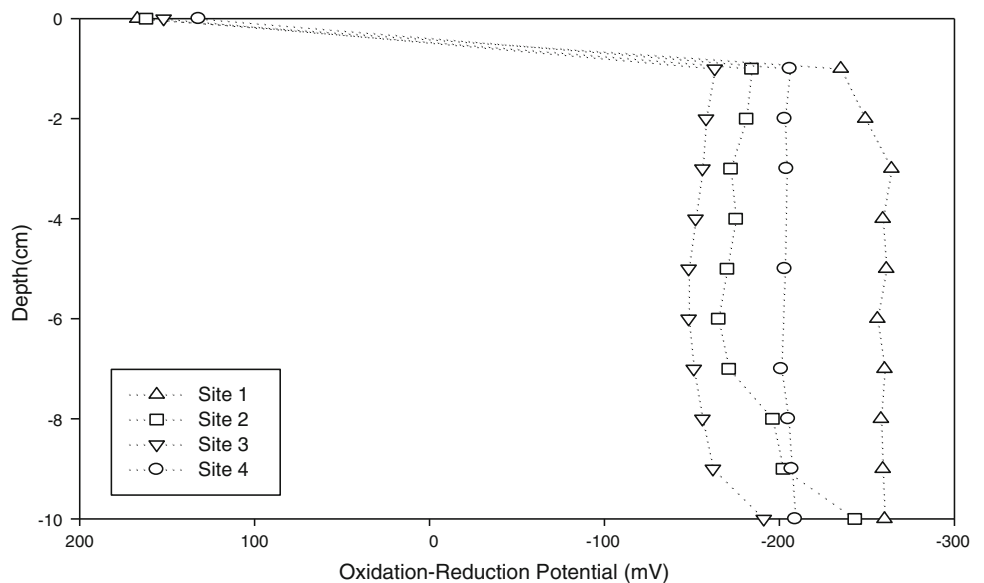
(c) Well No.3



**Fig. 7** ORP-mV varies with soil depth at four measurement sites in the experimental paddy field during the first crop period. **a** Measurements on 1 day before basal fertilizer application, and **b** measurements on 1 day after basal fertilizer application



**(a)** Measurements on one day before basal fertilizer application



**(b)** Measurements on one day after basal fertilizer application

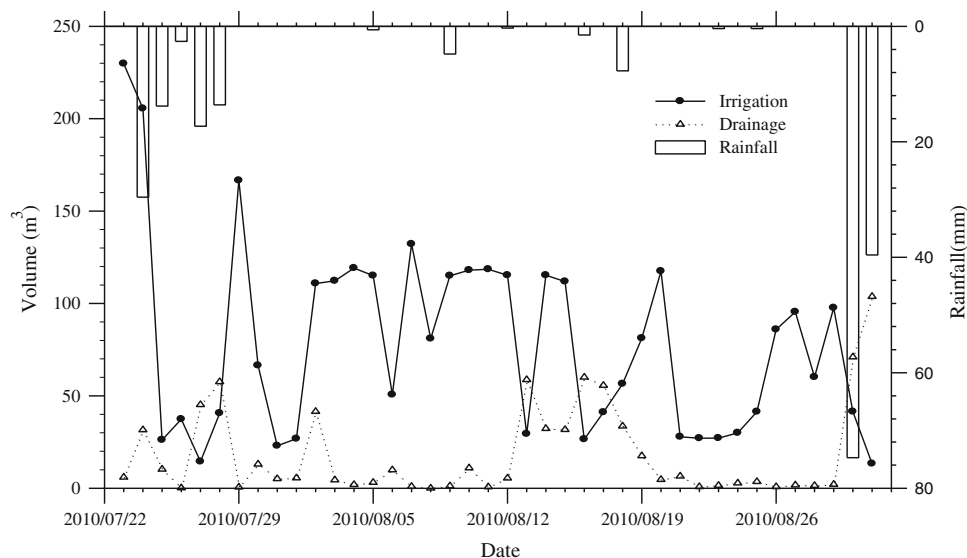
fertilizer dressing on the soil surface and plow into soil immediately, which is the conventional practice by the farmers in this area, only a small portion of fertilizer presented in the surface layer, namely, the oxidized region, and thus limit the nitrification reaction.

**Water management and N losses from paddy fields**

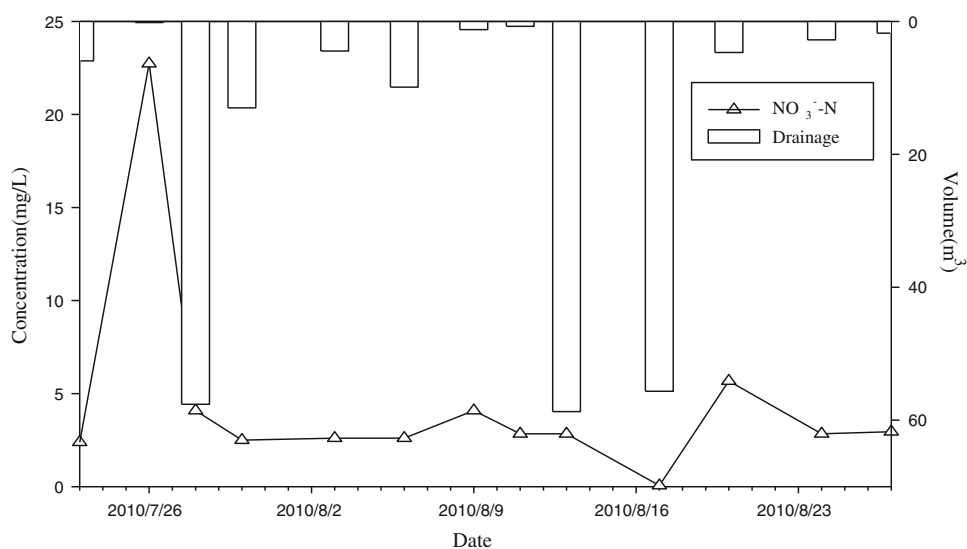
The ‘rotational irrigation’ scheme has proved to be an effective method for reducing water loss in Taiwan, while the continuous irrigation method typically results in excessive water loss and are frequently adopted in mountainous area. Thus, the continuous irrigation method required to be further assessed whether excessive water

loss occurs or not. In Taiwan, traditional farming practices emphasize no loss of fertilizer to other farmers’ fields. Surface drainage during non-storm periods should be minimized when farmers carefully conducted water management in fields. Evans et al. (1995) suggested that drainage control should be as one of the BMPs for reducing nonpoint source pollution. Figure 8 shows the water management by farmers in the experimental field during the fertilizer application period of second crop season. The amount of drainage was far less than that of irrigation during non-storm periods. Figure 9 shows the comparison between nitrate-N concentration and corresponding drainage volume during fertilizer application period of second crop period. The observed peak concentration of nitrate-N

**Fig. 8** Comparison between irrigation, drainage, and rainfall during fertilizer application period of the second crop season



**Fig. 9** Comparison between nitrate-N concentration and corresponding drainage volume during fertilizer application period of the second crop period



occurred on July 26th while almost no drainage occurs in the field. Investigation data showed that irrigation water was used efficiently in the studied paddy field. The amount of drainage during non-storm periods was significantly low, which confirmed that contamination potential of nitrate-N could be reduced for rice paddy culture in Taiwan.

The total amount of chemical N-fertilizer applied in this experimental paddy field ranged from 116 to 173% of nitrogen compared to the rational chemical fertilization rate for rice cultivation in north Taiwan (Agriculture and Food Agency 2005). The high fertilization rate also increased the risk of non-point pollution of nitrogen from terraced paddies. It is crucial to enhance the training of farmers to use fertilizers appropriately. Meanwhile some proper practices are suggested such as the use of organic

fertilizers and biofertilizers, planting green manures during fallow season to decrease the application amount of chemical N-fertilizer.

## Conclusions

The effects of N-fertilizer application on the return flow water quality of terraced paddy fields were assessed in this study. Observation results in the experimental terraced paddy field indicate that paddy fields would be a potential nonpoint pollution source of nitrogen, especially during the stage of basal fertilizer application which can contribute to the nitrogen enrichment of surface and groundwater systems. However, under proper control of drainage, even though the extensive continuous irrigation method is still

adopted in mountainous areas of Taiwan, measurement results showed that the amount of drainage during non-storm periods was significantly low. Moreover, fertilizer which dresses on the soil surface and plows into soil immediately during basal fertilizer application period would result in only a small portion of fertilizer presented in the oxidized region, and thus limit the nitrification reaction. The analyzed results confirmed that contamination potential of nitrate-N could be reduced for conventional rice paddy culture in Taiwan. However, because the rapid economic development has greatly reduced the amount of agricultural labor, the conventional agricultural management practices are facing challenge nowadays in Taiwan. Further investigations over a long-term period are suggested under diverse cultivation conditions.

**Acknowledgments** The authors would like to thank the Council of Agriculture, the National Science Council of the Republic of China for financially supporting this research under Contracts Nos. 99 Nou Fa-4.1-Li-05 (01) and NSC-100-2218-E-027-003-.

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